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# Rotation properties of feather shuttlecocks in motion

Xiaoshan Cao[1*], Jianmin Qiu[1], Xing Zhang[2], Junping Shi[1]

*1 Department of Engineering Mechanics, Xi'an University of Technology, Xi'an 710048, China*
*2Physical Department,, Xi'an University of Technology, Xi'an 710048, China*

**Abstract**

Feather shuttlecocks are chiral bodies whose rotation properties, such as trajectory and velocity, affect their motion states. This study proposes an experimental method to simulate the rotation properties of shuttlecocks. The effect of wind velocity on the angular velocity of refitting shuttlecocks is tested in a wind tunnel. The refitting parts lie on the cork of the shuttlecocks to avoid affecting the shape of the feather and the friction between air and the feather. Two types of moments are assumed to act on the shuttlecocks: driving and resistance. The driving moment is dependent on relative airflow velocity, whereas the resistance moment is related to rotation speed. Basing on wind tunnel experimental data, we illustrate the curves of the resistance and driving moments. Results provide theoretical guidance in the design of synthetic shuttlecocks and analysis of badminton techniques.



*Keywords:* chirality shuttlecocks; rotation speed; wind tunnel experiment; driving moment; resistance moment

## 1. Introduction

Badminton, one of the oldest sports in the world, originated in England in the 1880s and is now gaining popularity in Asia. Badminton has been an Olympic sport since 1992. Over 200 million amateurs and over a thousand professional athletes play badminton worldwide. The structures and dynamic characteristics of shuttlecocks, an essential instrument in badminton, have attracted the interest of researchers. Traditional shuttlecocks are made of duck or goose feathers. Synthetic shuttlecocks have been developed and manufactured since the 1950s. The flight properties of synthetic shuttlecocks differ significantly from those of feather shuttlecocks. Feather shuttlecocks are therefore used in most amateur badminton games and in all international competitive games.

Traditional shuttlecocks are chiral bodies, so their structures are non-identical to their mirror image. Synthetic shuttlecocks are always approximately centrally symmetric. The asymmetry of synthetic shuttlecocks provides


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stability during a game; however, asymmetry does not significantly affect velocity and trajectory. During high, clear shot testing, the landing point of a feather shuttlecock is closer than that of a synthetic shuttlecock, although the starting sections of their flight trajectories are coincidental. In fluid mechanics, the rotation property attributed to chirality affects the flight resistance of a feather shuttlecock in air.

Several studies have analysed the dynamics and flight trajectories of shuttlecocks. Chen et al. (2009) validated a motion equation for badminton events and found a relationship between air resistance force and shuttlecock speed. Alam et al. (2010) used an experimental method to measure the aerodynamic properties of a shuttlecock and compare the non-dimensional drag coefficient of feather and synthetic badminton shuttlecocks. Le Personnic et al. (2011) simulated the flight trajectory of synthetic and feather shuttlecocks at different wind speeds under non-spinning condition. Nakagawa et al. (2012) discussed the relationship between the aerodynamic properties and flow behaviour of a shuttlecock with spin rotation at high Reynolds numbers (Texier et al. 2012). However, these studies failed to consider shuttlecock rotations, which change air resistance. Cooke (2002) discussed the design parameters which affect the 2D motion of a shuttlecock in the trajectory plane and explained how these parameters are incorporated into a computer simulation tool to predict trajectories. The present study considers the effect of the moment of inertia (MOI), which is related to mass distribution. However, aside from MOI, the friction between the shuttlecock and air should also be considered in the design of a shuttlecock. The moment which acts on the shuttlecock can represent the macro behaviour of friction.

This study proposes an analytical model to examine the rotation speed of shuttlecocks. This model is used to measure the rotation behaviour of shuttlecocks. The effect of relative airflow velocity and rotation speed on the moments which act on the shuttlecocks is also analysed.

## 2. Experimental procedure

### 2.1. Refitting shuttlecocks

Figure 1 shows the structures of a traditional feather shuttlecock and a synthetic shuttlecock. The image shows that feather shuttlecocks are non-identical to their mirror image. When an arbitrary feather shuttlecock flies along the $z$-direction, the vector of the angular velocity must be along the positive direction of the $z$-axis. However, this phenomenon evidently does not exist in synthetic shuttlecocks.


Figure 1. Structure of a traditional feather shuttlecock.

To measure the rotation property of shuttlecocks, a refitting shuttlecock with similar bearings was designed. The shuttlecock should rotate along the axis in the wind tunnel. Axis friction is omitted in this study. To evaluate the rotational inertia of the refitting shuttlecock, a ring was manufactured as an additional mass (Figure 2). The rotational inertia is expressed as

$$J_0 = m_0 R_0^{\,2}$$

where $m_0$ and $R_0$ are the mass and radius of the ring, respectively, which are measured in the experiment. Hereafter, shuttlecocks 1 and 2 represent a refitting shuttlecock without and with an additional mass, respectively.

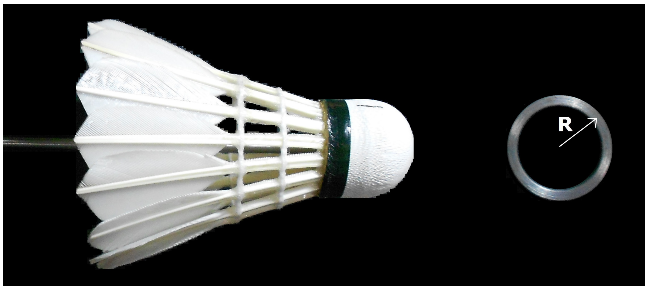



Figure 2. Refitting shuttlecock and an additional mass.

### 2.2. Theoretical model

To analyse shuttlecock speed, the effect of flow on the shuttlecock cork is omitted. The moment which acts on the feathers can be divided into two parts: driving and resistance. The driving moment is dependent on relative airflow velocity, whereas the resistance moment is a function of rotation speed. If the relation between the rotation speed and time is determined, the driving moment with respect to relative airflow velocity and the resistance moment with respect to the rotation speed can be obtained via derivation.

#### 2.2.1. Resistance moment

Consider a process in which the rotation of the shuttlecock slows down when the airflow in the wind tunnel is suddenly turned off. We assume that rotation speed is a function of time expressed as follows:

$$\omega_1 = \omega_1(t),\ \omega_2 = \omega_2(t), \tag{1}$$

where $\omega$ is the rotation speed, and subscripts 1 and 2 represent shuttlecocks 1 and 2, respectively.

The relationship of rotational inertia is

$$J_{r2} = J_{r1} + J_0\,, \tag{2}$$

where $J_{r1}$ and $J_{r2}$ are the rotational inertia of shuttlecocks 1 and 2, respectively.

Eq. (1) shows the relation between angular acceleration and rotation speed

$$\varepsilon_1 = \varepsilon_1(\omega_1),\ \varepsilon_2 = \varepsilon_2(\omega_2), \tag{3}$$

where $\varepsilon$ is the angular acceleration.

Resistance moment is a function of rotation speed. Therefore, the additional mass will not affect the resistance moment in the same rotation speed. When $\omega_1=\omega_2=\omega$, then

$$M_{r1} = M_{r2}\,, \tag{4}$$

where $M_r$ is the resistance moment.

The relation between moment $M$ and angular acceleration $\varepsilon$ is

$$M = J\varepsilon\,, \tag{5}$$

where $J$ is the rotational inertia.

Substituting Eqs. (3) and (5) into Eq. (4) yields

$$J_{r1}\varepsilon_1 = (J_{r1} + J_0)\varepsilon_2 . \tag{6}$$

Subsequently, the rotational inertia of shuttlecock 1 is

$$J_{r1} = \frac{\varepsilon_2 J_0}{\varepsilon_1 - \varepsilon_2} . \tag{7}$$

Substituting Eq. (7) into Eq. (5) yields the resistance moment

$$M_r = \frac{\varepsilon_2 \varepsilon_1 J_0}{\varepsilon_1 - \varepsilon_2} . \tag{8}$$

*2.2.2. Driving moment*

Similarly, we consider the rotation speed range from zero to a stable value when the airflow in the wind tunnel is suddenly turned off. The rotation speed, which is similar to flow speed *v*, can be recorded as follows:

$$\omega^*_1 = \omega^*_1(t) , \quad \omega^*_2 = \omega^*_2(t) , \text{ at the flow speed } v, \tag{9}$$

where $\omega^*$ is the rotation speed.

The relation between moment $M$ and angular acceleration $\varepsilon$ is expressed as

$$J\varepsilon = M_d - M_r , \tag{10}$$

where $M_d$ is the driving moment which is similar to the flow speed.

Similar to the derivation process in Section 2.2.1, we obtain the rotational inertia of shuttlecock 1 and the driving moment as follows:

$$J_{d1} = \frac{\varepsilon_2 J_0}{\varepsilon_1 - \varepsilon_2} , \; M_d = \frac{\varepsilon_2 \varepsilon_1 J_0}{\varepsilon_1 - \varepsilon_2} + M_r . \tag{11}$$

*2.3. Wind tunnel testing*

Wind tunnel testing can be divided into two parts. We recorded the rotation angle of refitting shuttlecock without and with an additional mass in the wind tunnel at different wind velocities to evaluate the relation between driving moment and wind velocity. We also recorded the relation between the rotation angle and time when the shuttlecock slows down at the moment when the airflow in the wind tunnel is suddenly turned off to determine the relation between the resistance moment and the rotation speed. Data on the refitting shuttlecocks without and with an additional mass are obtained.

## 3. Results and discussion

Figure 3 presents the rotation speed when the airflow in the wind tunnel is suddenly turned off. The rotational inertia of the shuttlecock with an additional mass is larger than that of the shuttlecock without an additional mass, such that the angular acceleration of the former is less than that of the latter.

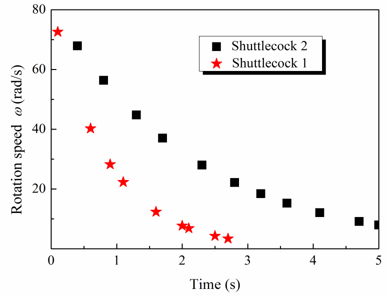



Figure 3. Rotation speed during deceleration.

In these experiments, the mass and diameter of the additional mass are 6.734 g and 29 mm, respectively. Therefore, the rotational inertia of the additional mass is 1415.8 g × mm$^2$. We calculate the resistance moment from these data and using Eqs. (7) and (8), as shown in Figure 4. The results show that resistance increases almost linearly as the rotation speed increases.

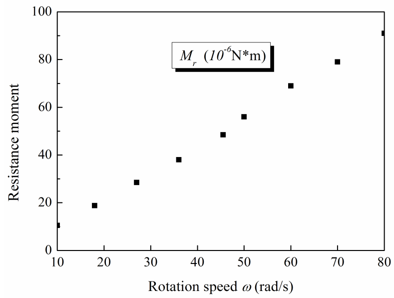
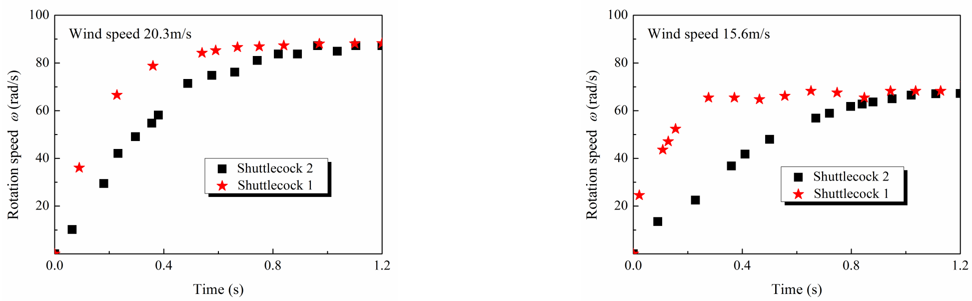



Figure 4. Resistance moment during deceleration.




(a) (b)

Figure 5. Rotation speed during acceleration. Wind speed: (a) 20.3 m/s. (b) 15.6 m/s

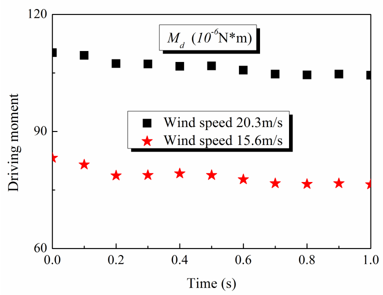



Figure 6. Driving moment during acceleration.

Figure 5 shows the relation between rotation speed and wind tunnel time. In these experiments, the rotation speeds vary from zero to a stable value. For shuttlecocks 1 and 2, the stable values of the rotation speed are similar. Therefore, the stable value of the rotation speed is assumed to be dependent on the wind velocity but independent of the rotational inertia. However, from zero to a stable value, shuttlecock 2 requires additional time. The driving moment is plotted as a function of time in Figure 6. The driving moment differs over the wind velocity but is almost similar to time. This result verifies that the driving moment can be determined by the relative airflow velocity.

## 4. Conclusions

Scientists consider the flight parameters of feather shuttlecocks in the design of synthetic shuttlecocks. However, previous studies failed to consider rotation properties. Aerodynamic theory states that the rotation of a flying object decreases flight resistance. When a player hits the shuttlecock, the flight and rotation speeds approach the maximum at the moment. Designing a synthetic shuttlecock based on the flight resistance data of feather shuttlecocks at this moment underestimates the flight resistance when the feather shuttlecocks slow down. This condition might be one of the reasons why the flight trajectories of feather and synthetic shuttlecocks initially exhibit good agreement but differ in landing points. The landing point of a synthetic shuttlecock is far from that of a feather shuttlecock. Furthermore, badminton techniques include normally and tangentially hitting the cork of the shuttlecocks. Knowledge on the rotation properties of shuttlecocks provides theoretical guidance on the design of novel synthetic shuttlecock structures and assists both amateur and professional players to understand the basic skills required for badminton.

## References

Alam, F., H. Chowdhury, C. Theppadungporn, H. Moria, and A. Subic. 2010. A comparative study of feather and synthetic badminton shuttlecock aerodynamics. 17th Australasian Fluid Mechanics Conference 2010, 17AFMC, December 5, 2010 - December 9, 2010, 17th Australasian Fluid Mechanics Conference 2010, pp. Olympus; COMSOL Multiphysics; LasTEK and LaVision; LEAP Australia; Kenelec Scientific.

Alam, Firoz, Harun Chowdhury, Chavaporn Theppadungporn, and Aleksandar Subic. 2010. Measurements of aerodynamic properties of badminton shuttlecocks. 8th Conference of the International Sports Engineering Association, ISEA, July 12, 2010 - July 16, 2010, vol. 2, pp. 2487-2492.

Chen, LM, YH Pan, and YJ Chen. 2009. A study of shuttlecock's trajectory in badminton. J Sports Sci Med 8, pp.657-662.

Cooke, A. 2002 Computer simulation of shuttlecock trajectories. Sport Eng. vol.5, Issue 2, pp. 93-105.

Le Personnic, J., F. Alam, L. Le Gendre, H. Chowdhury, and A. Subic. 2011. Flight trajectory simulation of badminton shuttlecocks. 5th Asia-Pacific Congress on Sports Technology, vol. 13, pp. 344-349.

Nakagawa, K., H. Hasegawa, M. Murakami, and S. Obayashi. 2012. Aerodynamic Properties and Flow Behavior for a Badminton Shuttlecock with Spin at High Reynolds Numbers. Engineering of Sport Conference 2012, vol. 34, pp. 104-109.

Texier, B. D., C. Cohen, D. Quere, and C. Claneta. 2012. Shuttlecock dynamics. Engineering of Sport Conference 2012, vol. 34, pp. 176-181.